



Air Force Research Laboratory



ADAPT

(Air Force Data Assimilative Photospheric Flux Transport)



Integrity ★ Service ★ Excellence

***Space Weather Workshop
Boulder, CO
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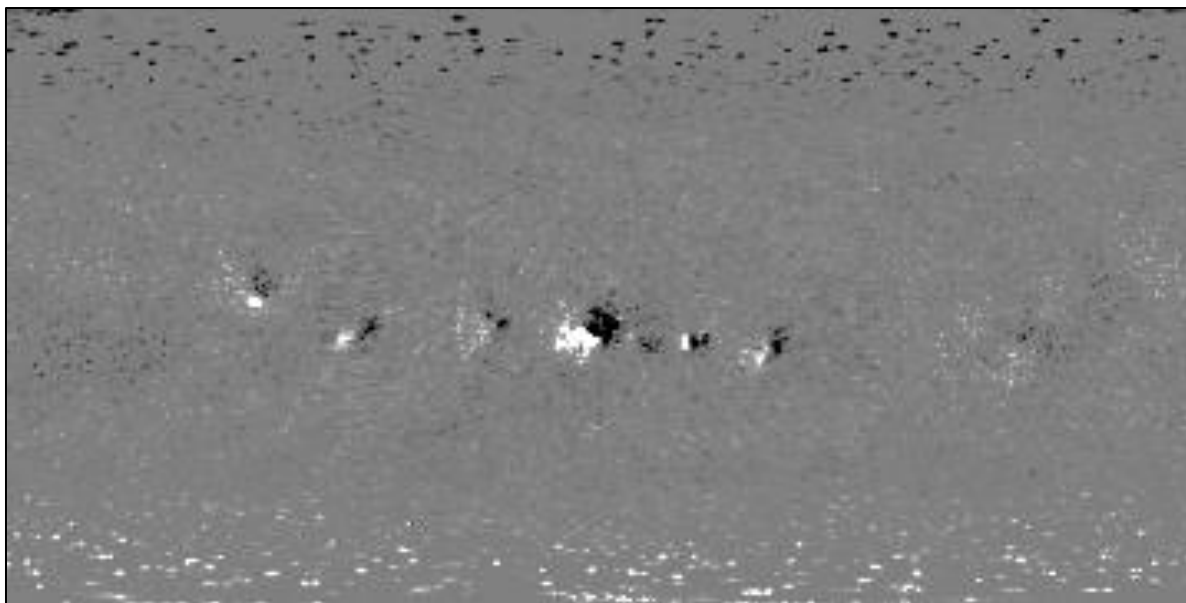
2. Los Alamos National Laboratory, Los Alamos, NM, USA



Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model



1. Evolves solar magnetic flux using well understood transport processes where measurements are not available.
2. Updates modeled flux with new observations using *data assimilation methods*
 - Rigorously takes into account model & observational uncertainties.



Sun's surface magnetic field (movie length ~60 days)

Provides more realistic estimates of the instantaneous global photospheric magnetic field distribution than those provided by traditional synoptic maps.



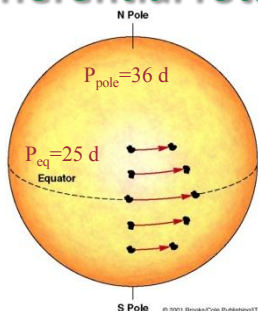
ADAPT Flux Transport Model



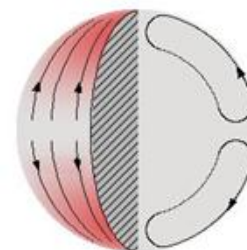
Overview: The ADAPT flux transport model (Arge et al. 2010, 2011, 2013; Henney et al. 2012 & 2014; Lee et al. 2013; Linker et al. 2013) is based on Worden & Harvey (2000), which *accounts for known flows in the solar photosphere*.

The modified Worden & Harvey (WH) model used in ADAPT includes:

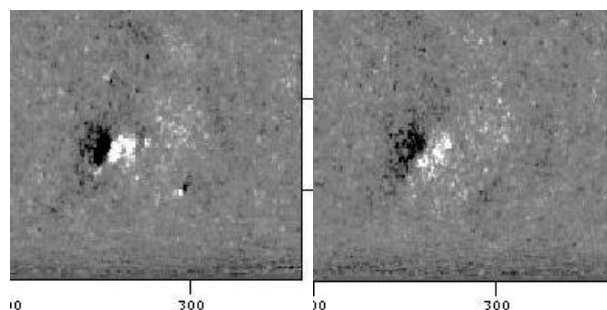
(1) Differential rotation



(2) Meridional flow



(3) Supergranular diffusion



(4) Random flux emergence

(5) Data assimilation of new observations (LANL)

(6) An ENSEMBLE of solutions representing the model parameter uncertainties



Data Assimilation



The ADAPT data assimilation method used: **Los Alamos National Laboratory (LANL) data assimilation framework.**

- Efficient and flexible data assimilation code.
- Uses either an Ensemble Least Squares or Kalman filter techniques.

1) Ensemble Least Squares (ENLS) estimation method:

- Method currently used most often.
 - Takes into account both model and data errors.
 - Does *not* consider spatial correlations.

2) Ensemble Transform Kalman filter (ETKF) method:

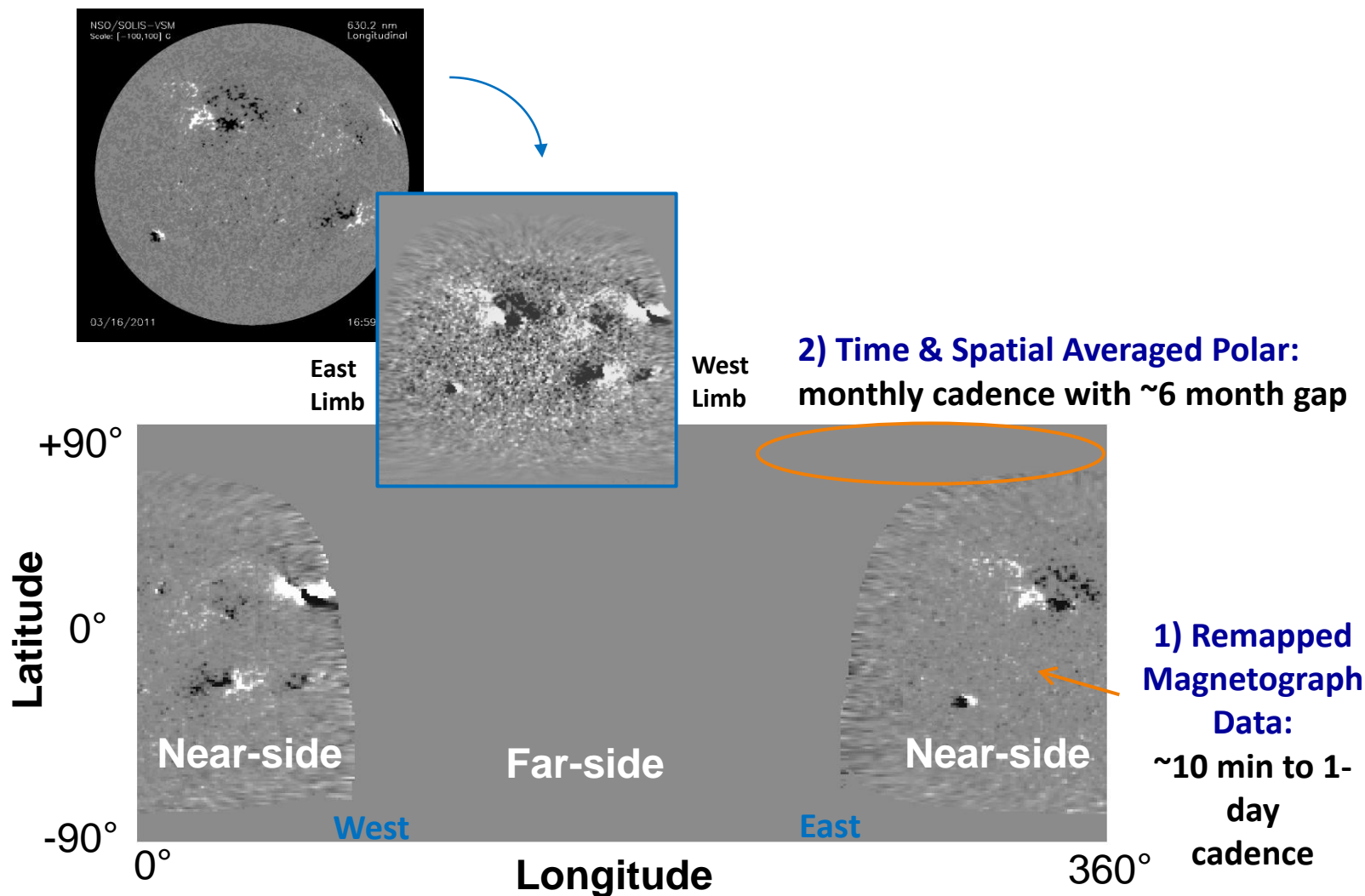
- Recursive algorithm that automatically takes into account *past correlations between different regions of the photosphere.*

3) Local Ensemble Transform Kalman Filter (LETKF) method:

- Localized version of the ETKF.
- Handles *unique* properties of solar magnetic field observations better.
- Recently incorporated.



Global Maps: Data Sources



New observation *at time* t_{obs}

Distribution A. Approved for public release; distribution unlimited





Example ENLS: model forecast

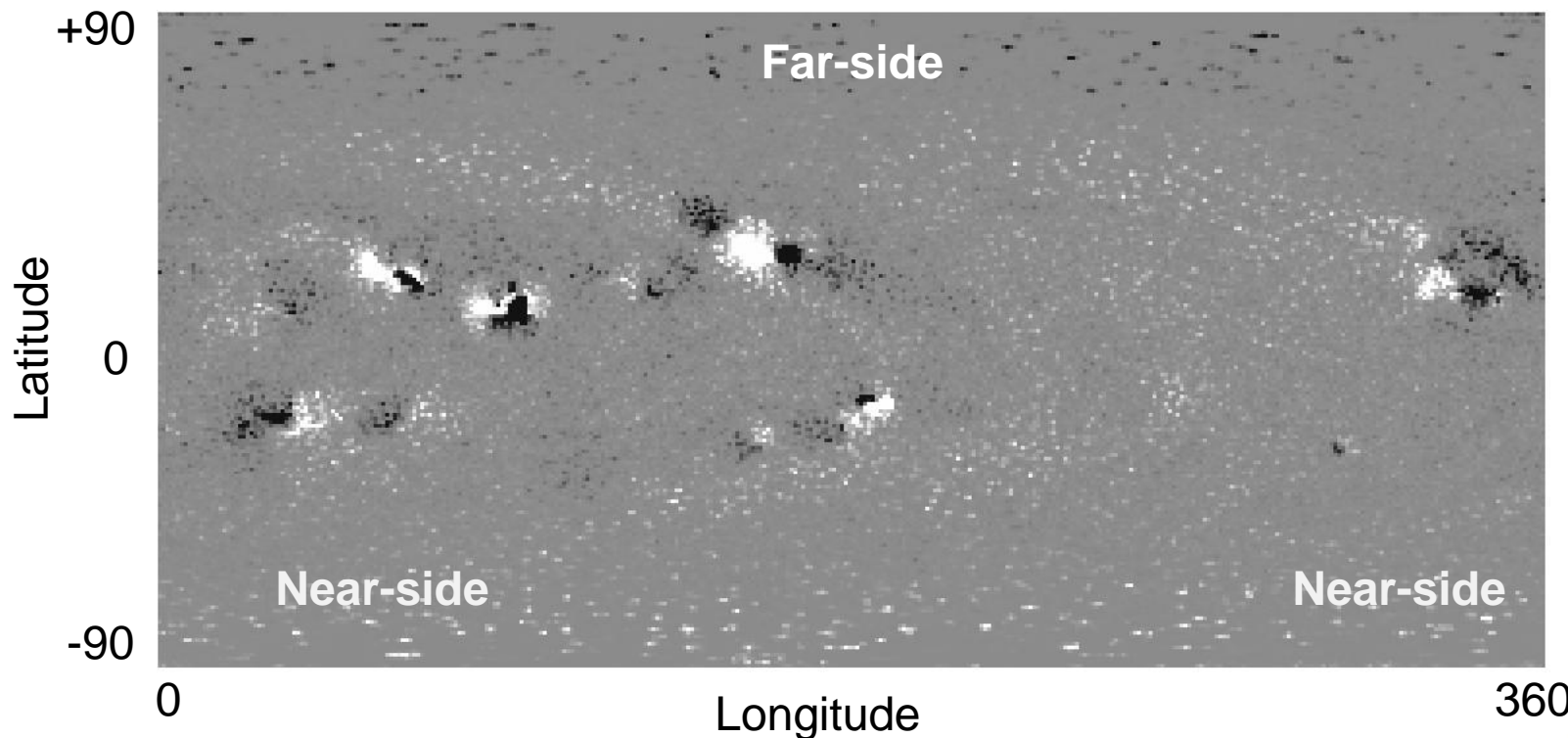


$$\text{Analysis} = X_a = X_f + \omega (y - H(X_f))$$

$$\text{Weight} = \omega = \sigma_f^2 / (\sigma_f^2 + \sigma_y^2),$$

(σ_f^2 and σ_y^2 are the variances of the model forecast ensemble & observed data respectively.)

Example forecast realization from the ensemble, X_f (at time t_{obs}):





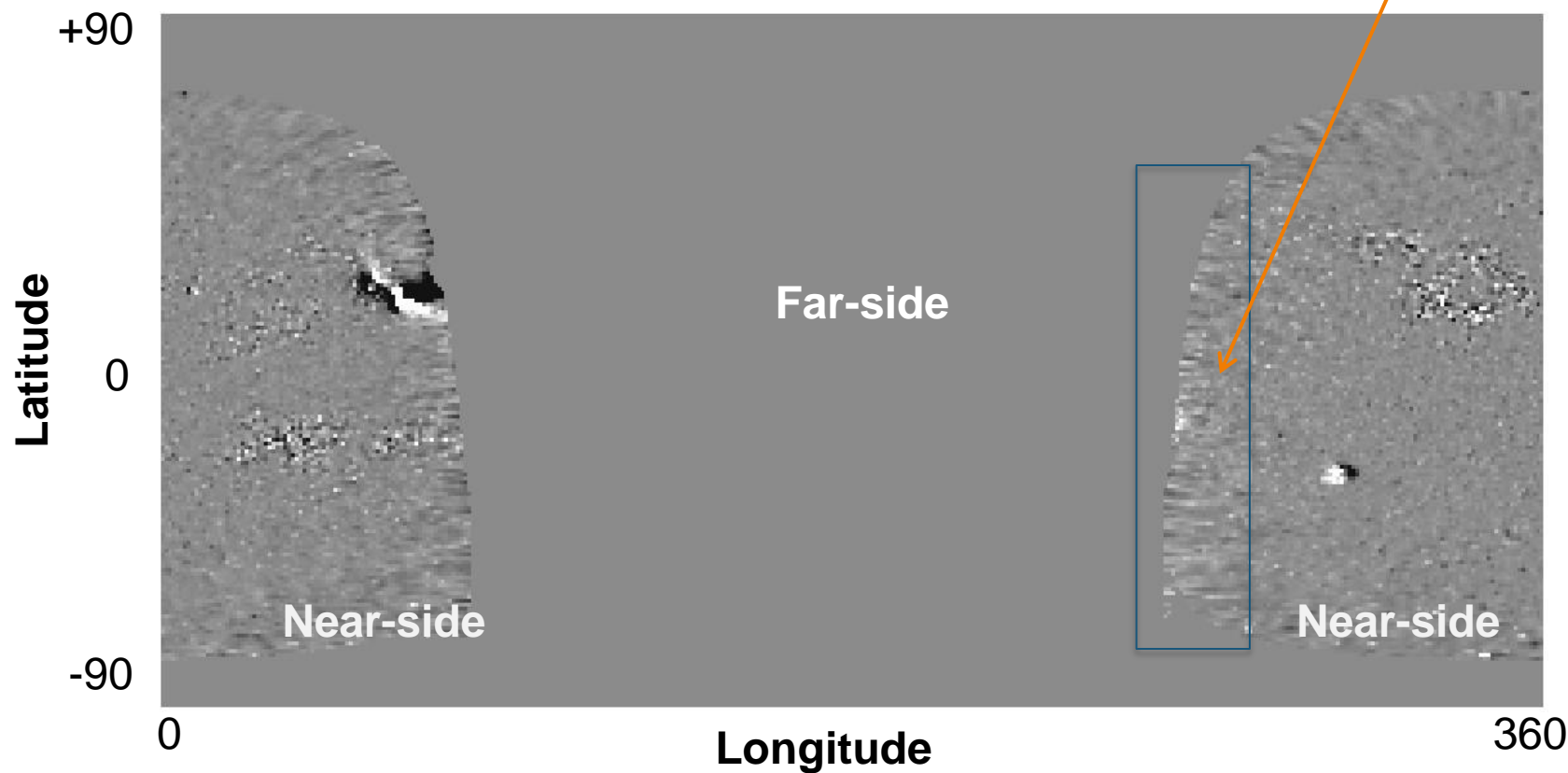
Example ENLS: Innovation



$$\text{Innovation} = \text{Observations} - \text{Model} = (y - H(x_f)),$$

at time t_{obs}

Solar East-limb:
region of > 13-day temporal discontinuity;
leads to large field strength/polarity offsets



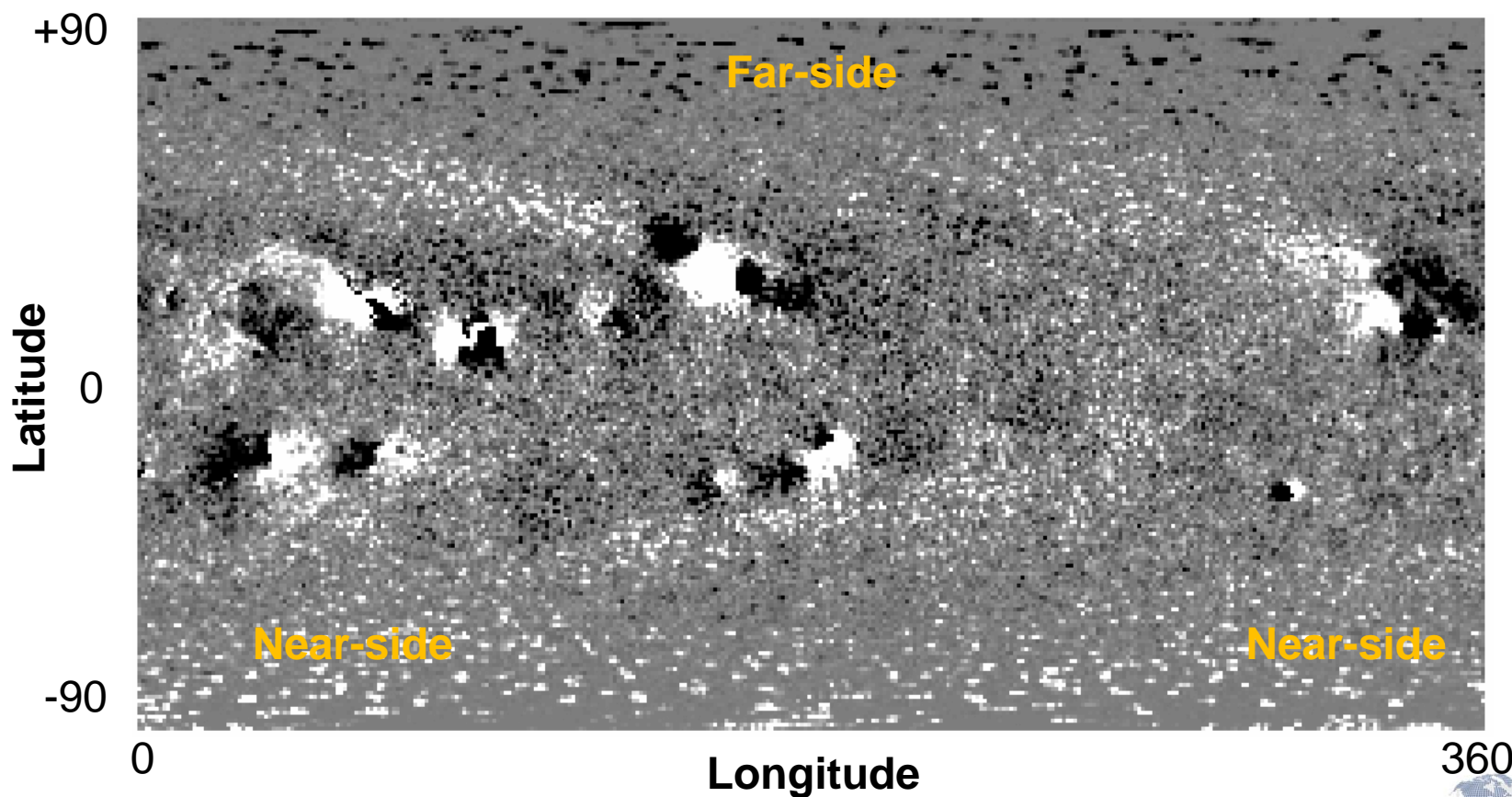


Example ENLS: analysis

$$\text{Analysis} = X_a = X_f + \omega (y - H(X_f))$$

$$\text{Weight} = \omega = \sigma_f^2 / (\sigma_f^2 + \sigma_y^2)$$

Example with 16 realizations (*at time t_{obs}*)

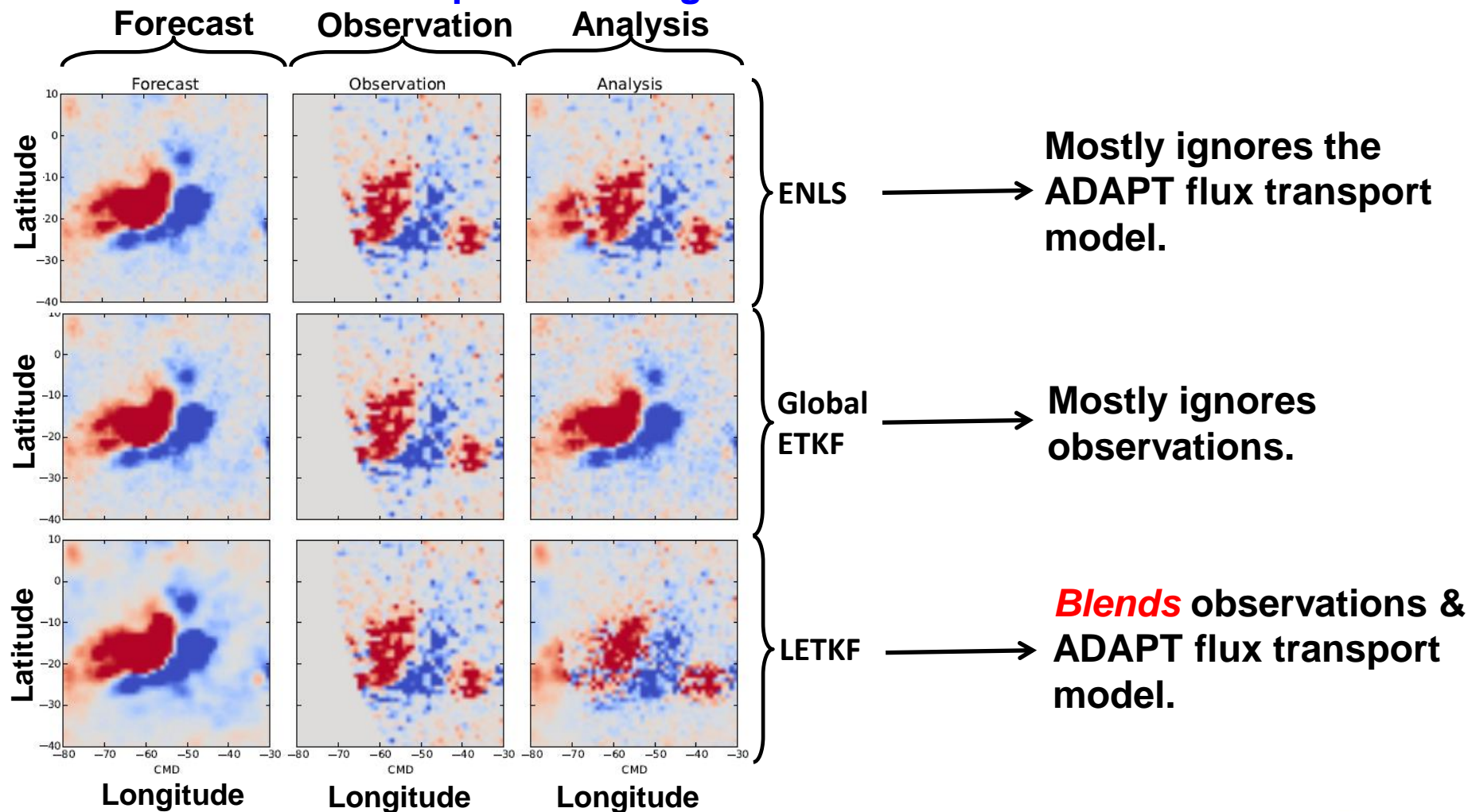




ADAPT Data Assimilation ENLS vs. Global & Local ETKF



Example Small Region of Data Assimilation



Hickmann et al. 2015, Solar Physics

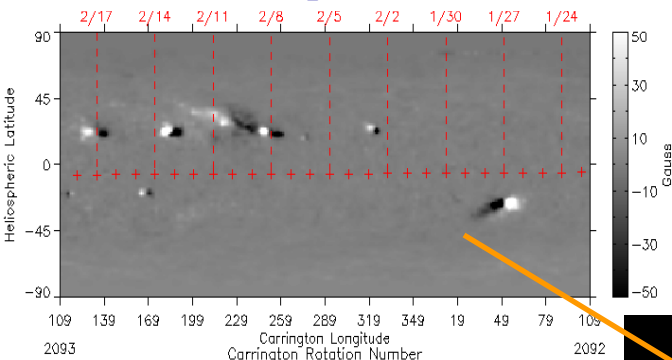
Distribution A. Approved for public release; distribution unlimited





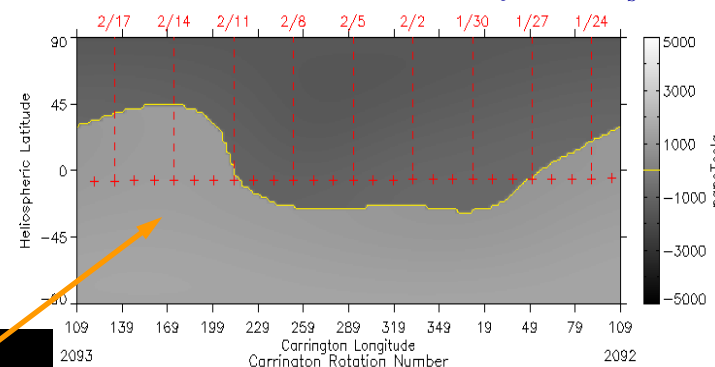
WSA Coronal Solution

MODEL INPUT: Observed Photospheric Field



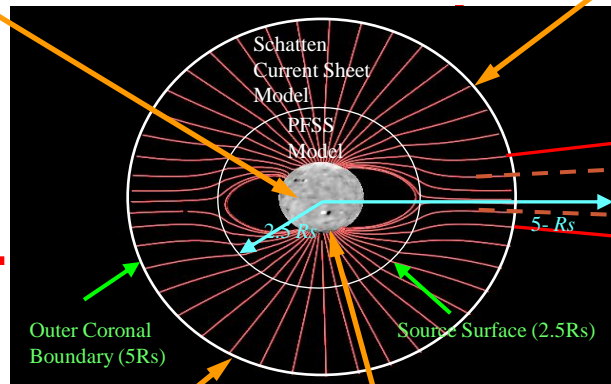
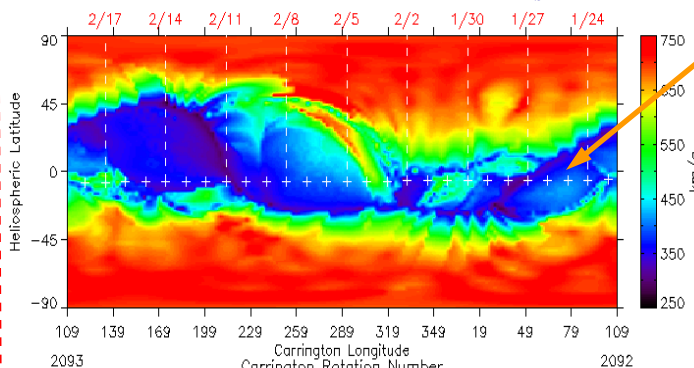
MODEL OUTPUT

Field at Outer Coronal Boundary ($5.0 R_s$)



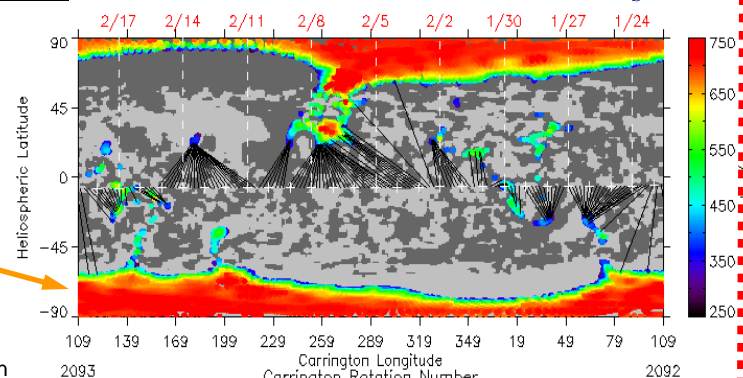
MODEL OUTPUT

Predicted Solar Wind Speed ($5.0 R_s$)



Solar Wind Model
(e.g., WSA 1D Kinematic model, Enlil,
LFM-Helio, & HAF)
(5-30 R_s to 1AU)

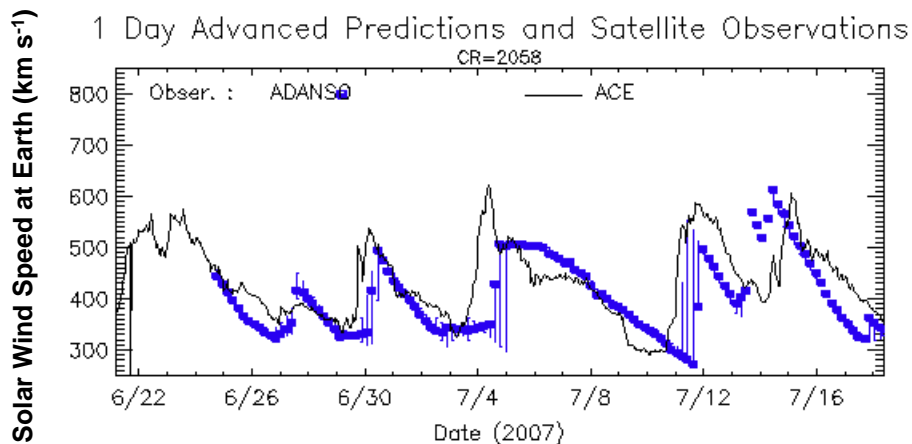
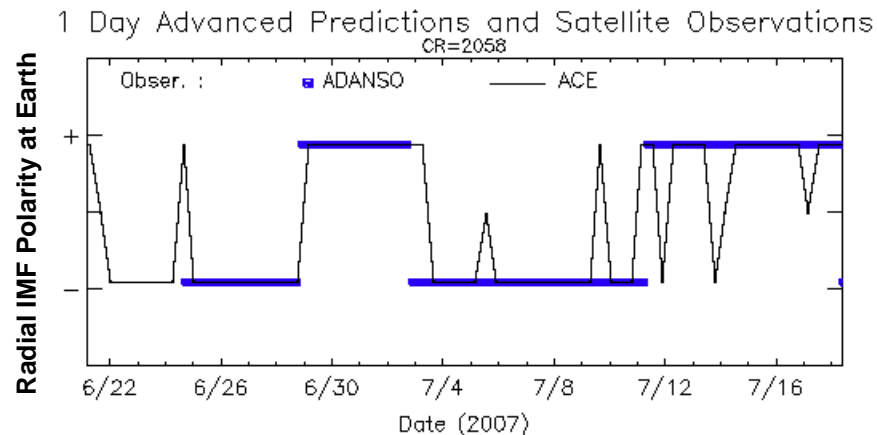
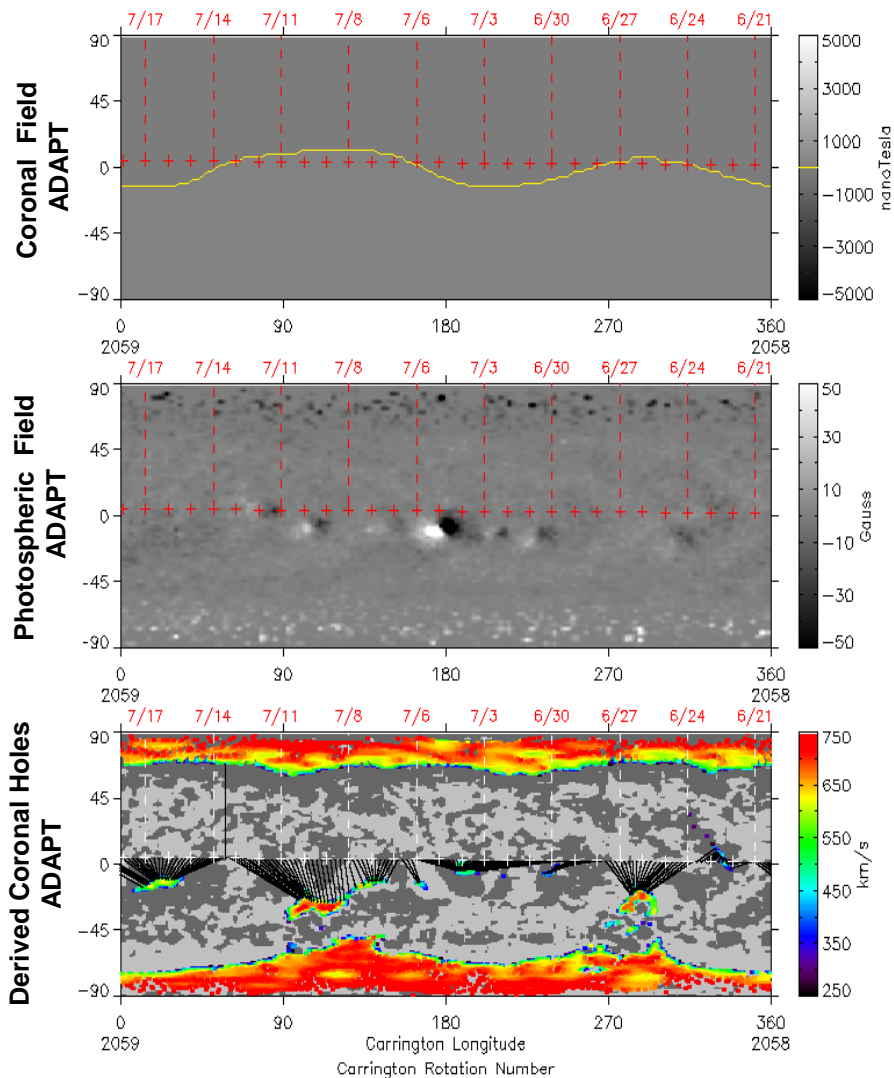
Derived Coronal Holes ($1.0 R_s$)



MODEL OUTPUT

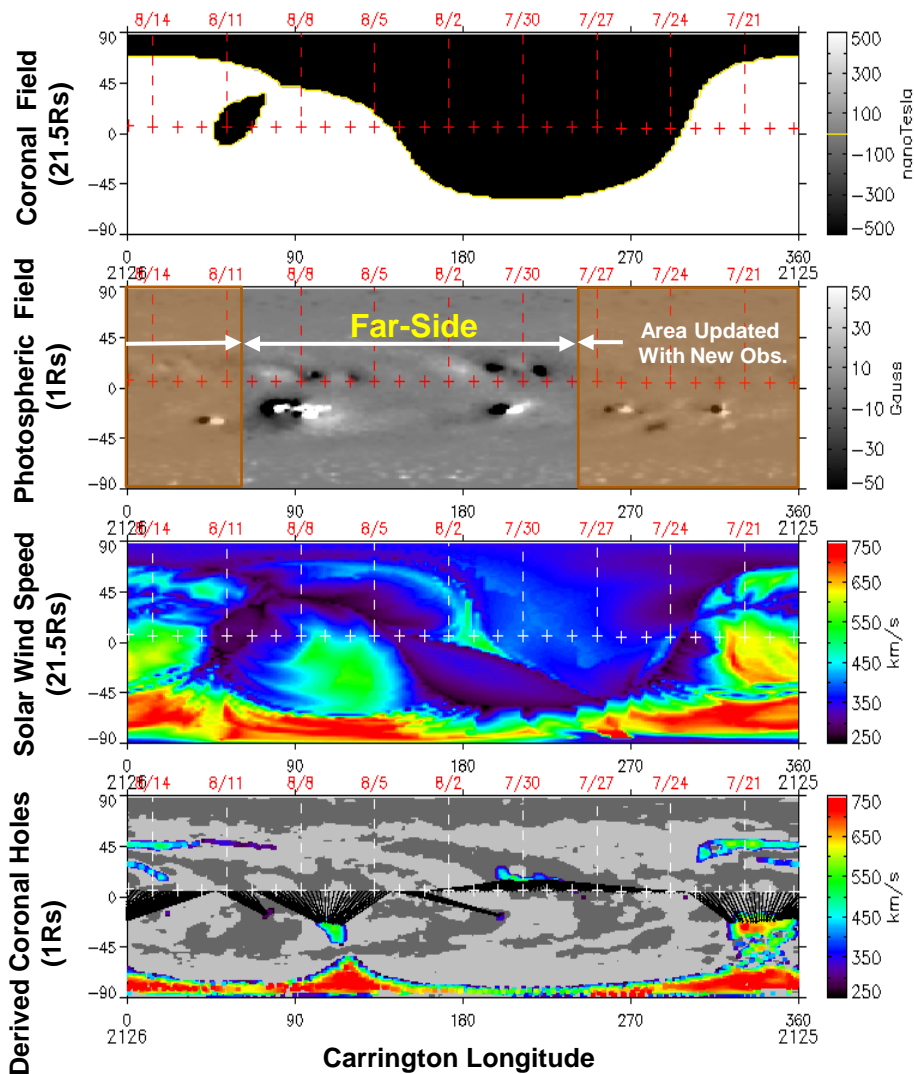


WSA Coronal & Solar Wind Solutions using the 12 ADAPT Realizations for June 21, 2007 (Start of CR2058)

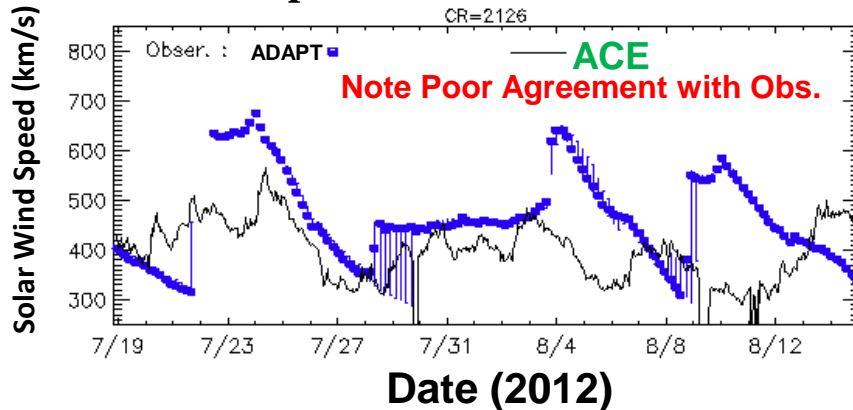




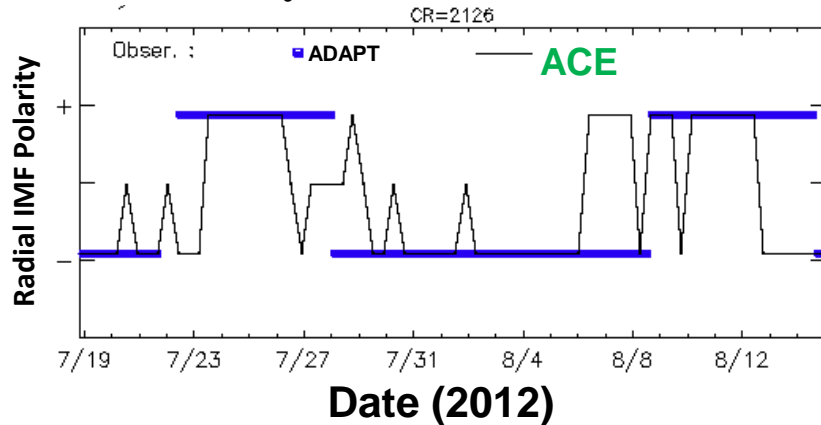
WSA Coronal and Solar Wind Predictions Using July 21, 2012 ADAPT Map as Input to WSA



Solar Wind Speed Predictions vs Observations



IMF Polarity Predictions vs Observations

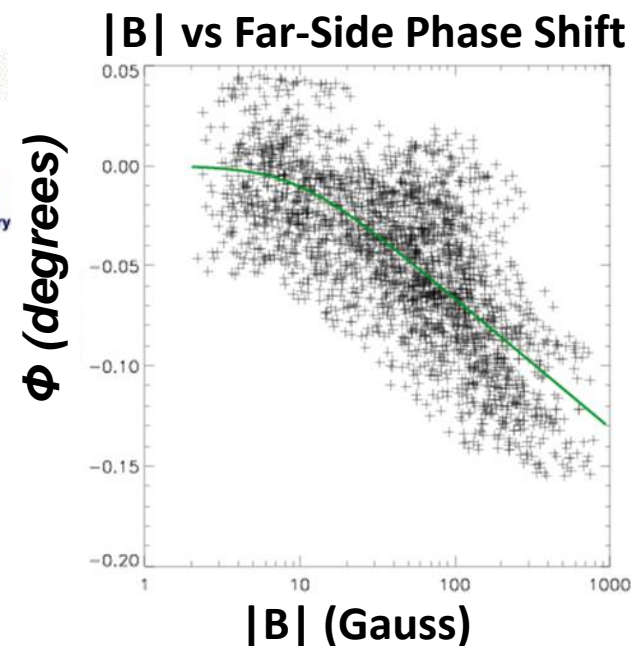
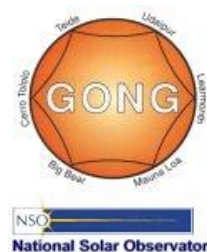
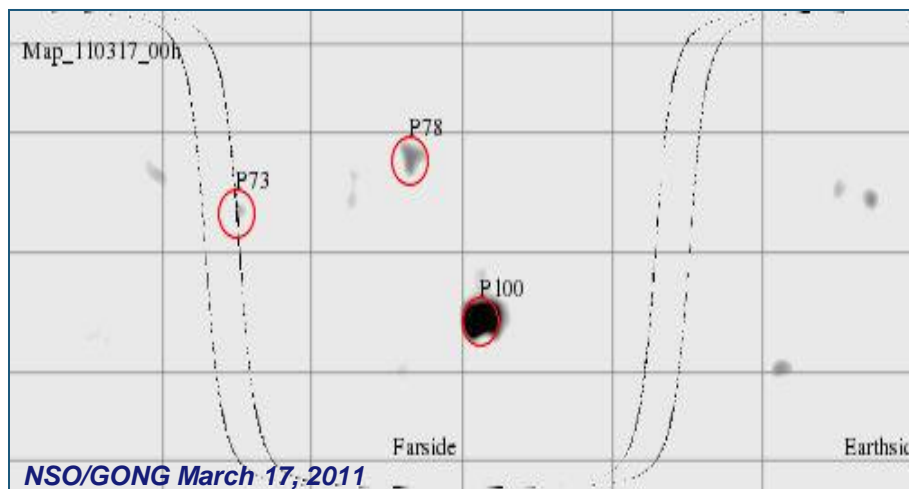




Incorporating Far-side Maps



Without far-side data, space weather forecasting models are reliant on the persistence & recurrence of past observations.



(Gonzalez-Hernandez et al., 2007)

Far-side data assimilation requires a realistic estimation of the:

1. magnetic field strength & uncertainty
2. position & uncertainty
3. simple polarity & tilt estimations (i.e., Hale's law & Joy's Law, other approaches)

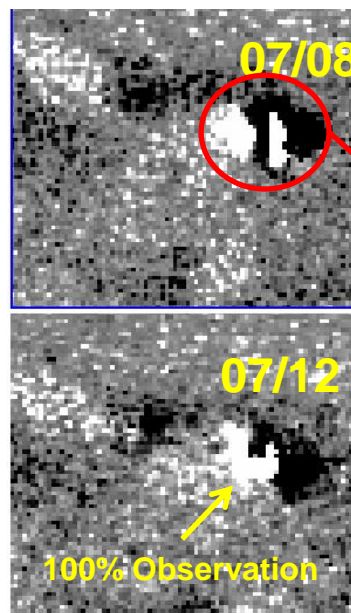
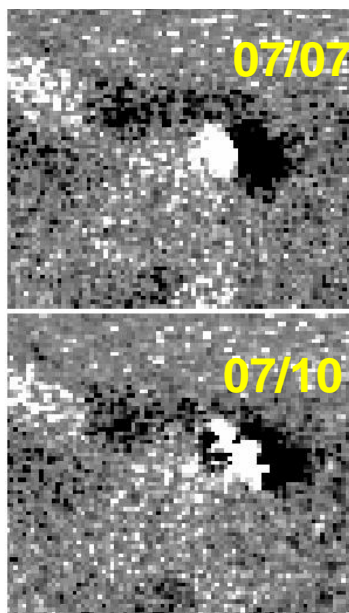
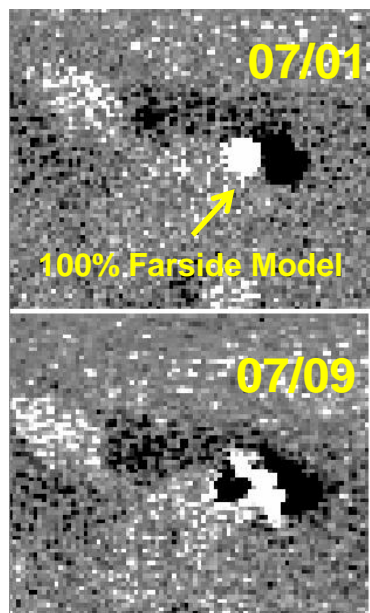
A “far-side ensemble” can be generated from these 3 factors.



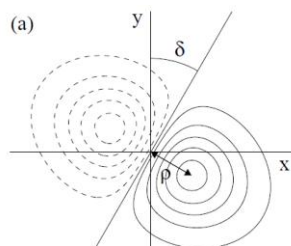
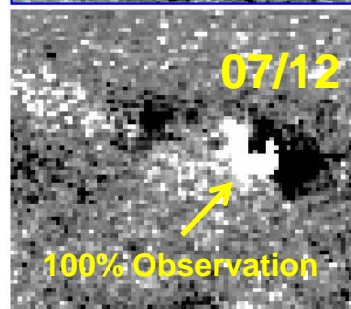
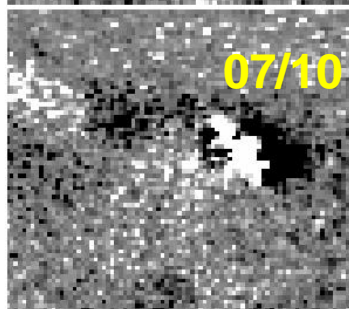
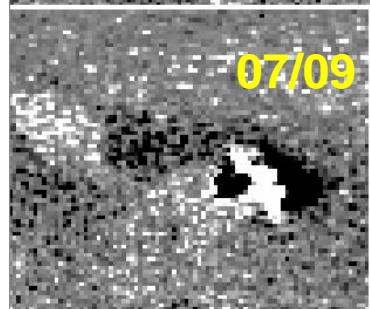
Generate Smoothly Evolving Solar Global Magnetic Maps



Example evolution of the farside signal within ADAPT maps. The farside model estimation is merged on July 1st. The first observation is assimilated on July 8th. The final frame, July 12th, is nearly 100% observation, whereas the July 7th image is 100% far-side & ADAPT flux transport model values.



Localized non-physical magnetic monopoles often result in global magnetic maps during the data assimilation process!



Investigate methods to:

- 1. Forward model far-side detected helioseismic active regions (e.g., Yeates et al, 2007).**
- 2. Reverse model near-side active regions.**
- 3. Use near & far-side detections together to produce smooth evolution.**

Yeates et al., 2007

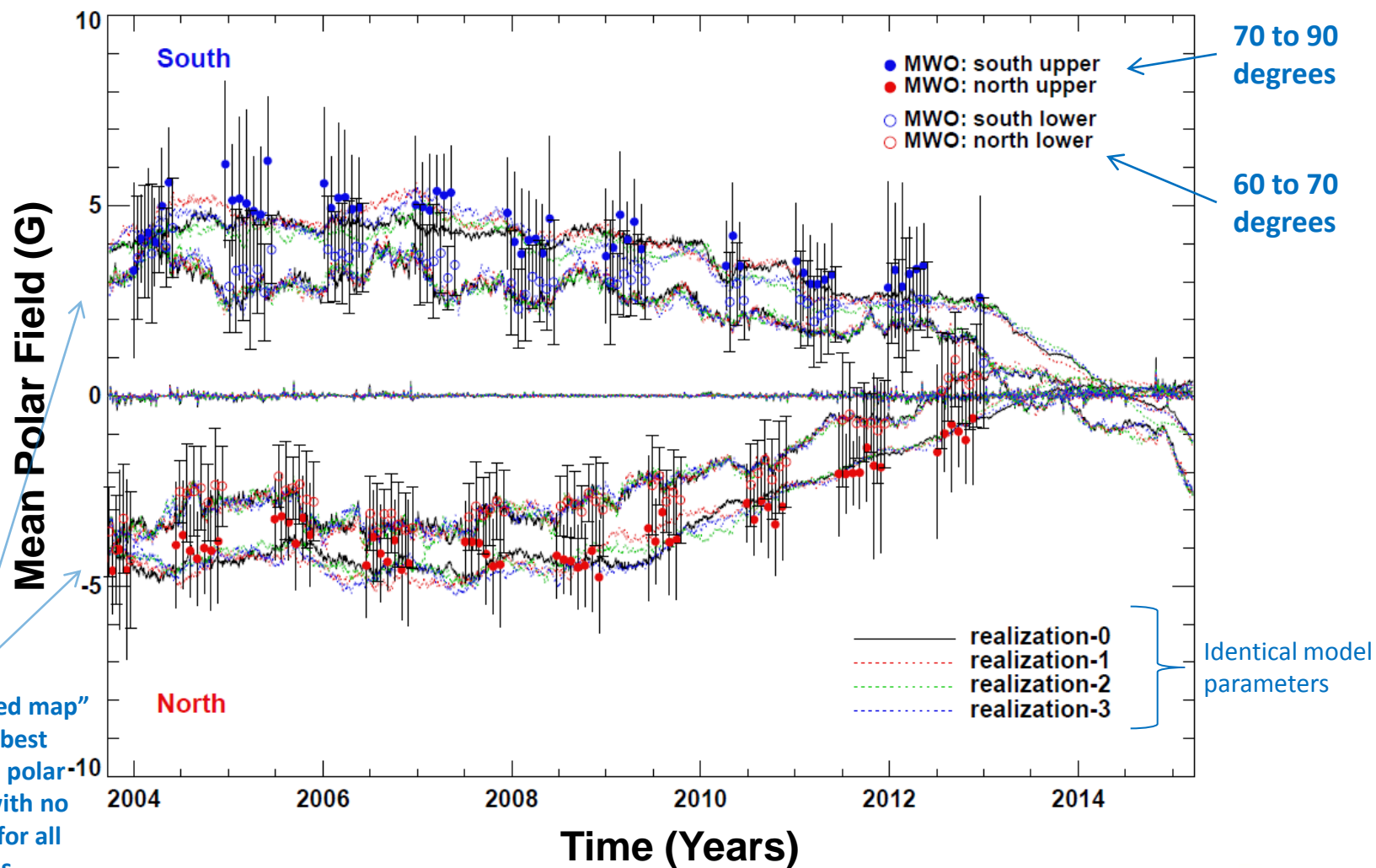
$$B_r = -B_0 e^{0.5 \frac{x}{\rho}} \exp \left[- \left(\frac{x^2/2 + y^2}{\rho^2} \right) \right]$$

Distribution A. Approved for public release; distribution unlimited





ADAPT Polar Fields



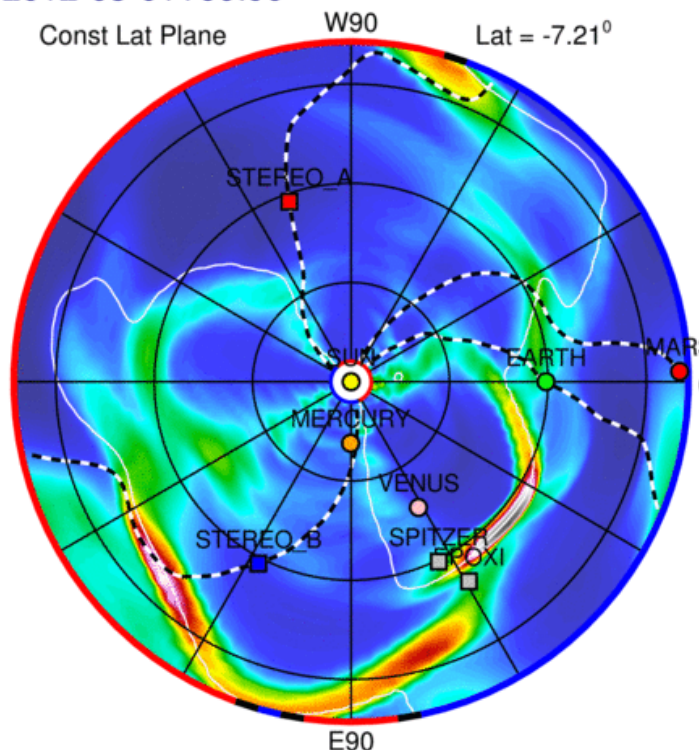


“Time-Dependent” ADAPT-WSA-Enlil (Driven by GONG magnetograms)



2012-03-01T00:00

Const Lat Plane W90 Lat = -7.21°

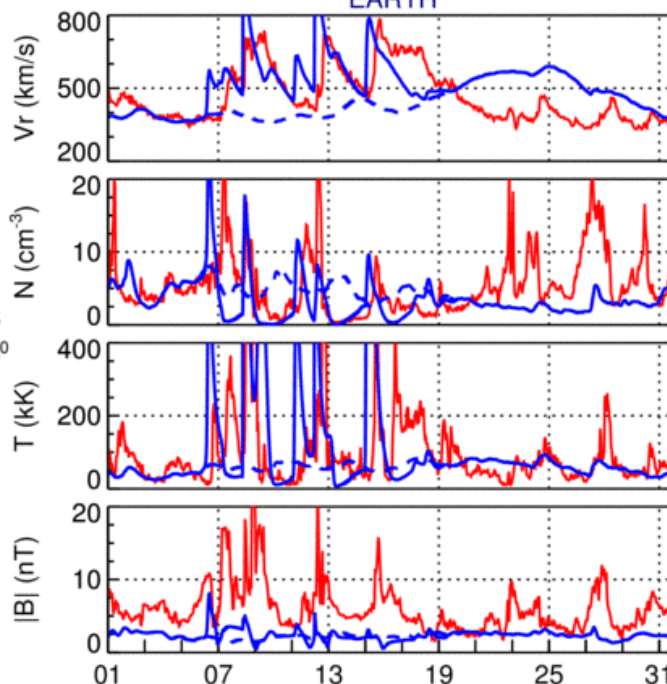


$R^2 N \text{ (cm}^{-3}\text{)}$ 0 10 20 30 40 IMF polarity - +

ENLIL-lowres + AGN-WSADA + Cone-SWRC

2012-03-01T00 + 0.00 days

EARTH



ACE

ADAPT-WSA-Enlil
Forecast

ADAPT-WSA-Enlil
Forecast with CMEs

2012-03 / 2012-04

HCS IMF line CME measured simulated

HELIO WEATHER

Moving toward time-dependent ADAPT-WSA-Enlil solar wind forecast capability



$F_{10.7}$ & UV Empirical Models



The $F_{10.7}$ & UV empirical models, based on Henney et al. 2012, use the near-side magnetic field estimates from the ADAPT maps:

$$F_{\text{model}} = m_0 + m_1 S_P + m_2 S_A$$

where

$$S_P = \frac{1}{\sum \omega_\theta} \sum_{25\text{G} < |B_r|}^{|B_r| < 150\text{G}} |B_r| \omega_\theta$$

Solar radial magnetic field from ADAPT

Solar Weak Field [“**Plage**”]

$$S_A = \frac{1}{\sum \omega_\theta} \sum_{150\text{G} \leq |B_r|} |B_r| \omega_\theta$$

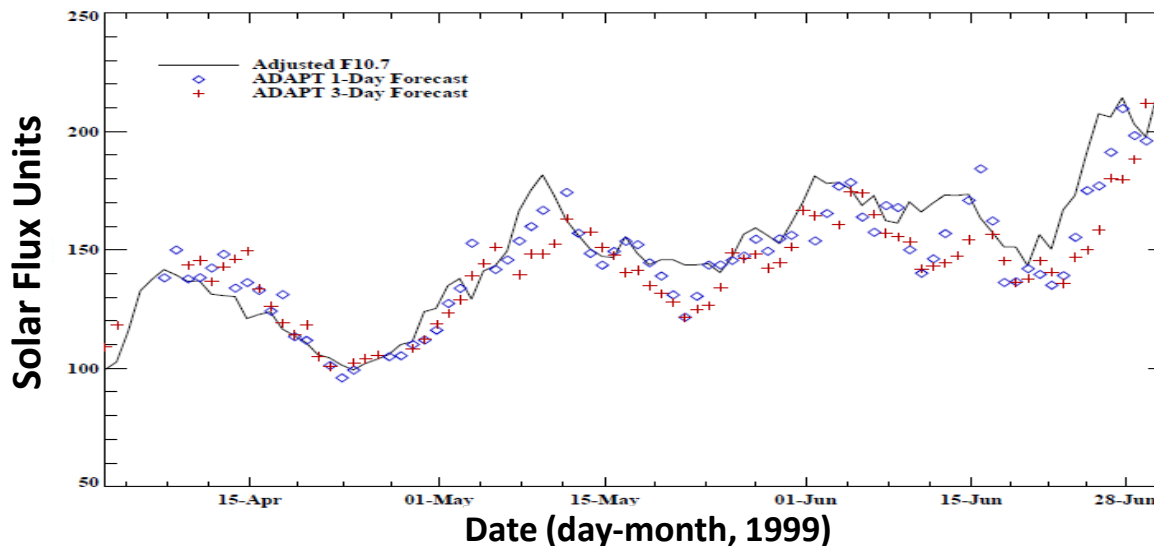
Solar Strong Field [“**Sunspot**”]

$F_{10.7}$ modeling: Henney et al. 2012, *Space Weather*, **10**, S02011

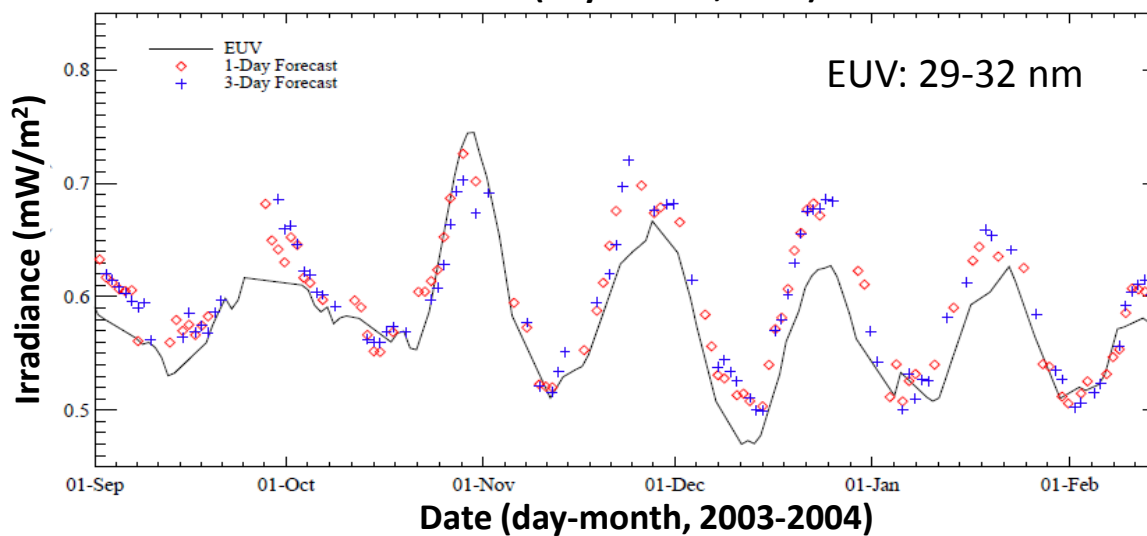
VUV modeling: Henney et al. 2015, *Space Weather*, **13**, doi:10.1002/2014SW001118



Forecasting $F_{10.7}$ & EUV with ADAPT



$F_{10.7}$



EUV: 29-32 nm

EUV



ADAPT $F_{10.7}$ Forecast Status



- The ADAPT model is currently running 24/7 at the National Solar Observatory (NSO).
- ADAPT global maps are generated every 2 hours, utilizing NSO/GONG magnetograms.

[ftp://gong2.nso.edu/adapt/maps](http://gong2.nso.edu/adapt/maps)

- ADAPT 1 to 7 day $F_{10.7}$ forecast values, updated every 2 hours, are publically available at:

[ftp://gong2.nso.edu/adapt/f10/](http://gong2.nso.edu/adapt/f10/)

Example ADAPT $F_{10.7}$ Forecast File

```
Product : adapt_f107_forecast.txt
Created : 2014 10 24 2147 UT
Date : 2014 10 24
DOY : 297
Model: ADAPT-F10.7
Version : 5.0212
POC : CJ Henney (USAF/AFRL)
POC Email : adapt@nso.edu
Data Input : GONG
Resolution [deg / pixel] : 1.00
Fit-function : m0 + m1*M_P + m2*M_A
Forecast : 0, 1, 3, 7
m0 : 66.08, 65.00, 64.00, 63.00
m1 : 8.51, 8.00, 9.00, 10.00
m2 : 16.56, 17.00, 18.00, 19.00
M_P (plage mag-field) Lower Limit [G] : 25.0
M_A (active region mag-field) Lower Limit [G] : 150.0
Missing Value : -1.0
Record Count : 12

# Table Notes
#
# JD - Julian Date
# M - Missing = 0 - forecast available
#           = 1 - forecast missing or pending
# Q - Quality = 0 - input data nominal
#           = 1 - entry with >2 days w/o model input data
# H - Helioseismic data within forecast window:
#     = 0-none, 1-farside, 2-nearside, 3-both farside & nearside
# UT - forecast time, Coordinated Universal Time, HHMM format
# LastMag - fractional days since last mag data assimilation
# NearF10 - fractional days since last F10 obs differenced w/ od value
# Diff - obs_model offset = (F10.7 obs value) - (0-day model prediction)
# F10.7 Forecast - 0day, 1day, 3day, 7day model estimates plus diff offset

# Observed F10 Data Source
#
# http://www.swpc.noaa.gov/ftpdir/lists/radio/7day_rad.txt

# ADAPT - F10.7 Forecast [s.f.u. @ earth distance]
#
# JD M Q H UT LastMag NearF10 Diff 0d 1d 3d 7d
#-----
2456954.5000 0 0 0 0000 0.087 0.042 33.0 202.0 207.2 212.4 144.0
2456954.5833 0 0 0 0200 0.011 0.125 33.0 204.9 209.9 214.8 144.7
2456954.6667 0 0 0 0400 0.004 0.208 33.0 204.2 209.1 213.9 143.9
2456954.7500 0 0 0 0600 0.087 0.292 33.0 203.1 208.5 212.5 143.0
2456954.8333 0 0 0 0800 0.171 -0.375 52.9 222.0 227.8 231.0 162.3
2456954.9167 0 0 0 1000 0.254 -0.292 52.9 221.0 227.4 230.5 161.7
2456955.0000 0 0 0 1200 0.338 -0.208 52.9 220.1 227.1 230.0 161.4
2456955.0833 0 0 0 1400 0.421 -0.125 52.9 219.3 226.7 229.4 161.3
2456955.1667 0 0 0 1600 0.504 -0.042 52.9 217.7 226.5 228.6 160.9
2456955.2500 0 0 0 1800 0.587 0.042 52.9 215.7 226.3 228.0 160.8
2456955.3333 1 1 0 2000 -1.000 -1.000 -1.0 -1.0 -1.0 -1.0 -1.0
2456955.4167 1 1 0 2200 -1.000 -1.000 -1.0 -1.0 -1.0 -1.0 -1.0
```



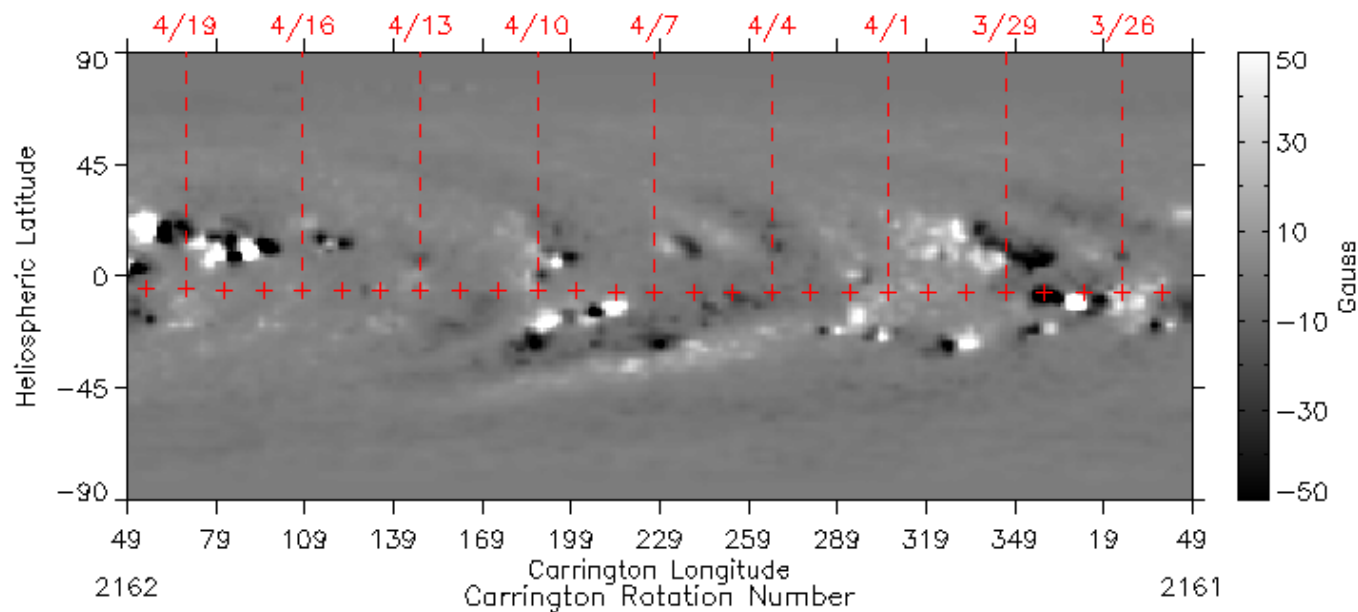
Summary



1. ADAPT is a data assimilative, photospheric magnetic field flux transport model.
 - Provides “instantaneous snapshots” of the Sun’s global magnetic field as input for coronal, solar wind, F10.7, and EUV models.
2. Implemented & testing the advanced LETKF data assimilation methodology in ADAPT and comparing the results with older approaches (ENLS & ETKF).
 - Initial comparisons between 3 different assimilation methods made (*Hickmann et al. 2015, Solar Physics*)
3. Incorporating helioseismic far-side active region data into ADAPT model.
4. Working to generate *temporally smooth* evolving solar global magnetic maps.
5. Moving toward ADAPT driven, time-dependent WSA+Enlil solar wind model.
6. *Coronal & solar wind solutions VERY sensitive to the photospheric magnetic field Boundary Conditions.*
7. ADAPT maps and F10.7 forecasts available via NSO.
 - Global maps: <ftp://gong2.nso.edu/adapt/maps>
 - 1-7 day $F_{10.7}$ forecast values: <ftp://gong2.nso.edu/adapt/f10/>



Observed Photospheric Field from National Solar Observatory/GONG

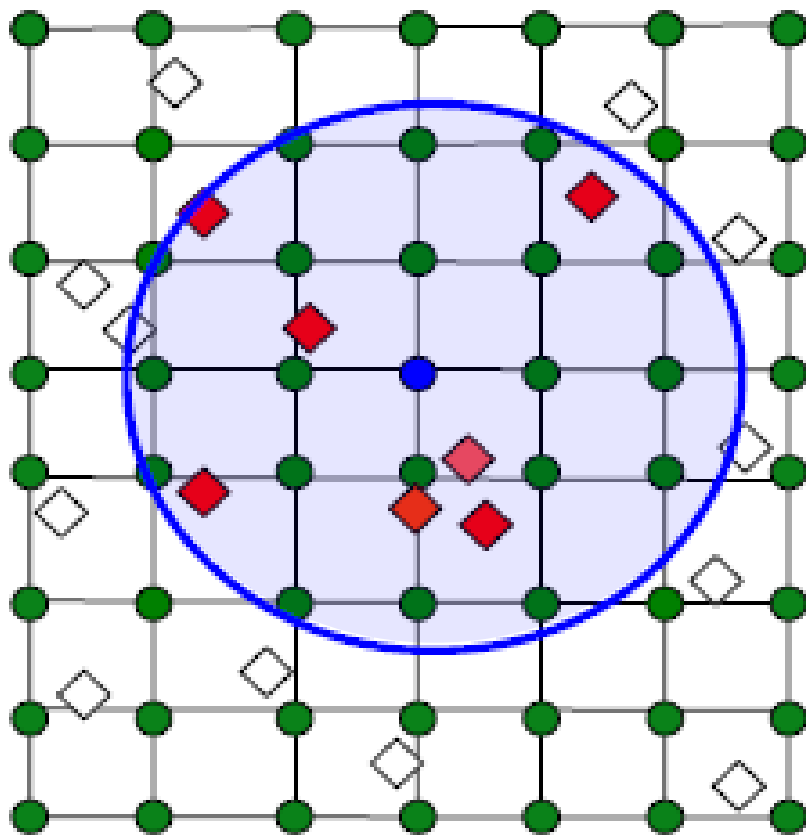


Created 2015 Apr 16 225 UTC

NOAA/SWPC, BOULDER, CO, USA



Localized Ensemble Transform Kalman Filter Assimilation

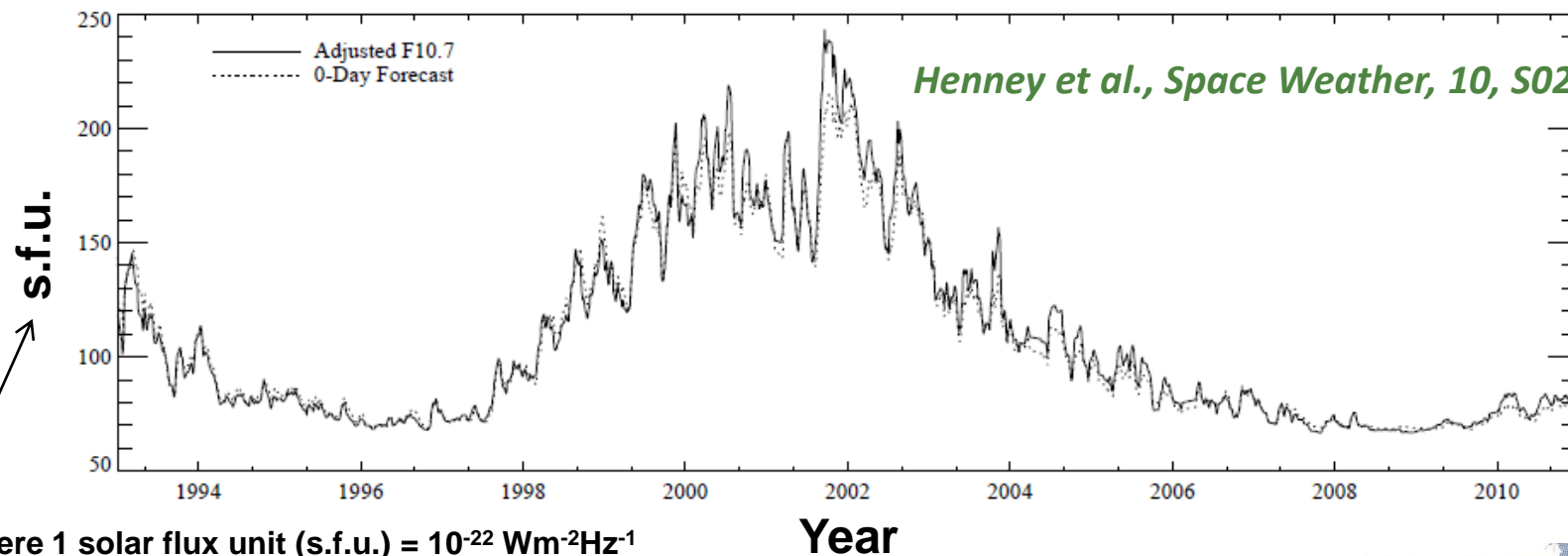
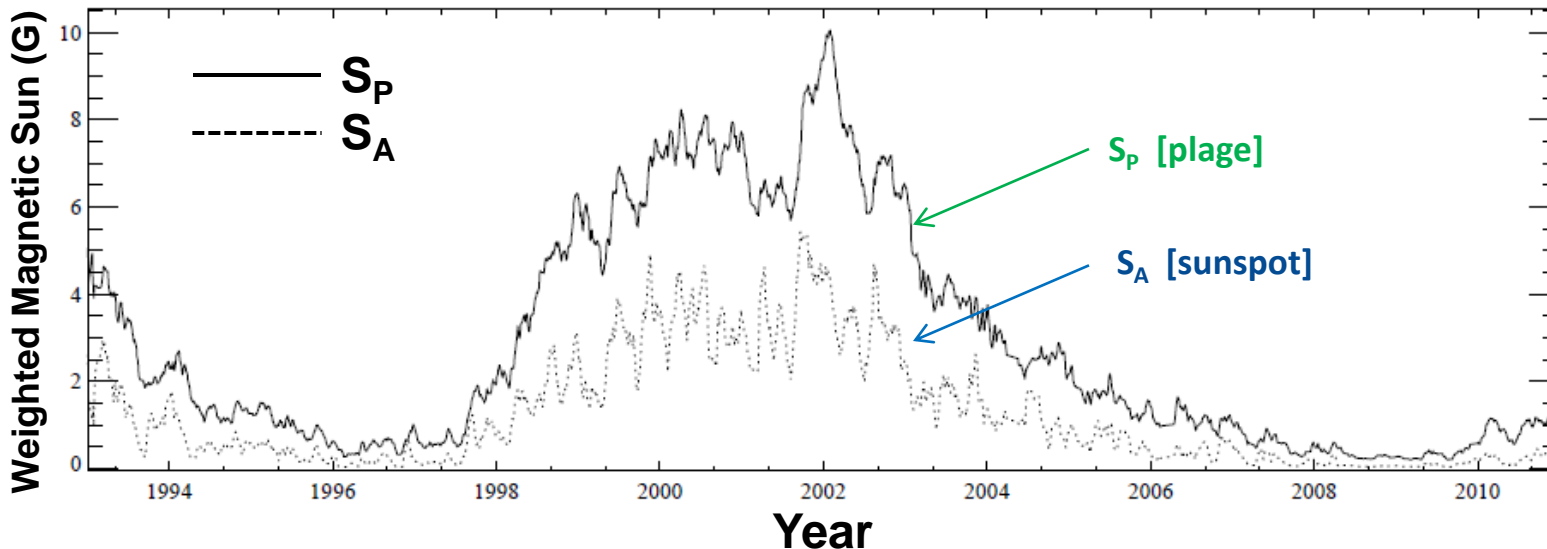


The LETKF algorithm assimilates one model grid-point at a time (blue dot) by defining a local area of interest (blue circle) and identifying any observations that fall within the local region (red diamonds).

- Localized version of the ETKF
- Each gridpoint of spatial domain updated with local observations residing in local domain of interest
- Domain defined by model dynamics & assumptions of correlations between discrete model gridpoints
- Eliminates all long-range spurious correlations
 - Delivers cleaner solution and suppresses noise
- Algorithm highly parallel since all gridpoints can be assimilated simultaneously



ADAPT $F_{10.7}$ Model



Henney et al., Space Weather, 10, S02011, 2012

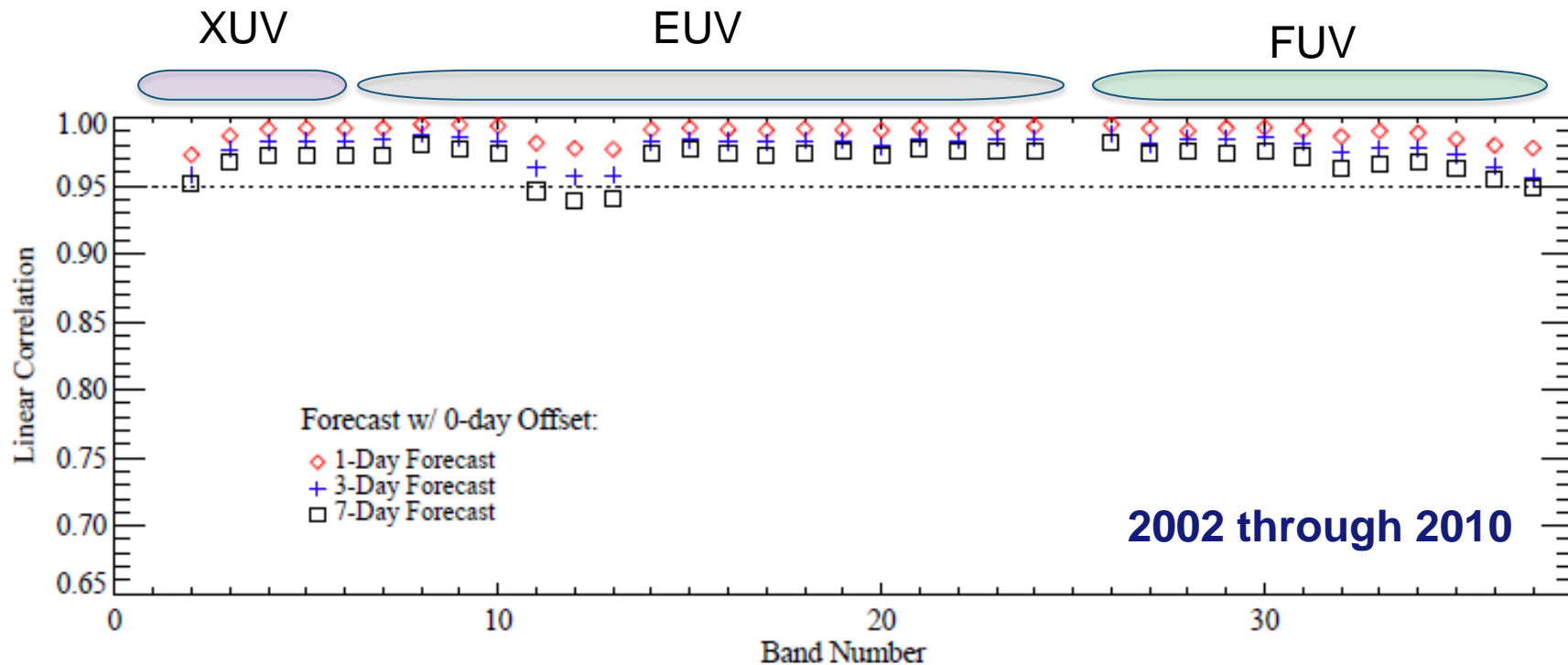


ADAPT $F_{10.7}$ & VUV

Advance Forecast Correlations

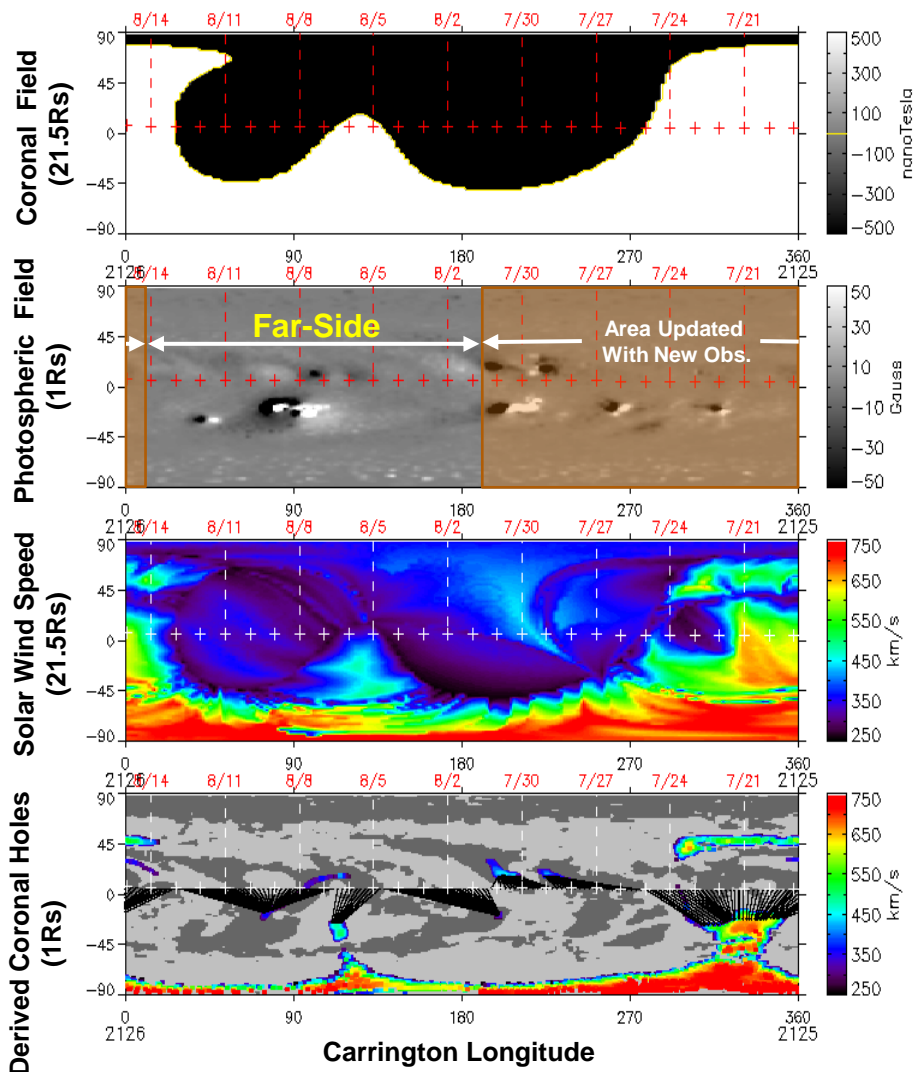


$F_{10.7}$ forecast - 1, 3, and 7 day advance: .99, .97, .95

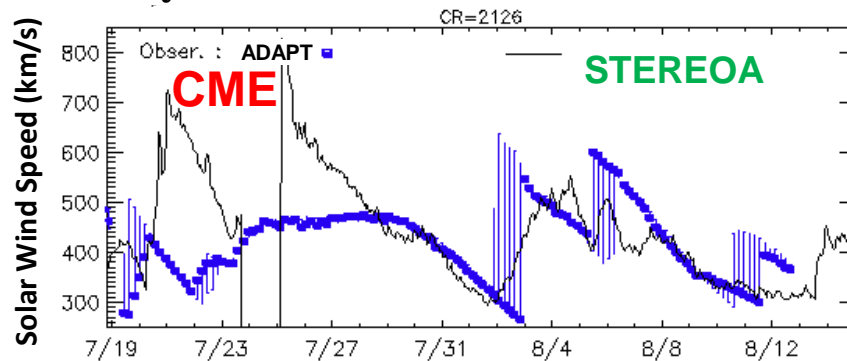




WSA Coronal and Solar Wind Predictions Using *July 25, 2012* ADAPT Map as Input to WSA

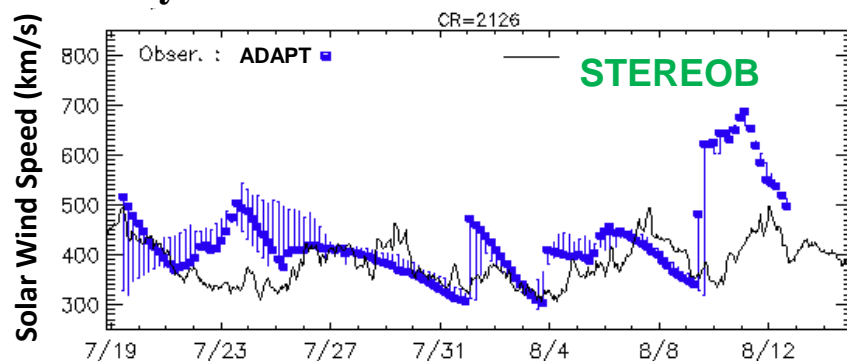


4 Day Advanced Predictions vs Observations



Updated 7-26-2013 Date (2012)

4 Day Advanced Predictions vs Observations



Updated 7-25-2013 Date (2012)